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Advancing Circularity in Additive Manufacturing: Life Cycle Assessment of Post-Consumer PA12 Recycling

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Abstract: Additive Manufacturing (AM) has emerged as a transformative technology in industrial production, enabling the fabrication of complex geometries with reduced material waste compared to conventional methods. Among its techniques, Powder Bed Fusion (PBF) is widely applied to polymeric materials such as polyamide 12 (PA12), producing durable components that eventually reach end-of-life. The growing volume of discarded AM parts highlights the need for sustainable end-of-life strategies, with mechanical recycling offering a promising pathway to close material loops within a circular economy. This study evaluates the environmental performance of post-consumer PA12 recycling from prototypes and parts manufactured via PBF using the HP Multi Jet Fusion 5210 printer. The assessment followed ISO 14040 and 14044 guidelines, adopting a cradle-to-gate boundary and a functional unit of 1 kg of recycled PA12 pellets (PA12r). Data were based on primary measurements at SENAI/CIMATEC's facilities, complemented by secondary datasets from Ecoinvent 3.10.1. The product system comprised five stages: Cascalheira Milling, Cimatec Park Milling, Manual Washing, Drying, and Extrusion/Pelletizing. Life Cycle Impact Assessment (LCIA) results, focused on Global Warming Potential (GWP100, IPCC 2021), showed PA12r achieved a 10% carbon footprint reduction compared to virgin PA12. Drying was the most impactful stage in total emissions, while Extrusion/Pelletizing had the highest hourly rates, underscoring their critical roles in optimization. Electricity consumption was the dominant contributor, influenced by equipment demand and Brazil's energy mix. Findings show the technical and environmental potential of scaling PA12 recycling for additive and conventional manufacturing, while addressing a literature gap and supporting recycling integration in AM supply chains to boost circularity and reduce impacts.

Keywords: 3D printing, PBF, carbon footprint, circular economy.

1.Introduction

Additive Manufacturing (AM) has gained prominence in the industrial landscape due to its ability to revolutionize the design and production of components, offering flexibility for manufacturing complex geometries with greater material efficiency. Unlike conventional processes, which generally involve machining or molding by removing material, AM builds parts layer by layer, reducing waste and enabling greater design freedom. Among the various AM techniques, Powder Bed Fusion (PBF) stands out for using a powder bed selectively fused by thermal energy, as defined by ASTM 52900:2021. This technology is widely used with polymeric materials such as polyamides, producing durable products that eventually reach the end of their useful life, requiring appropriate disposal solutions, such as recycling, to re-enter the production chain. These processes must be evaluated in terms of environmental aspects and impacts to ensure environmental gains with the technology [3].

In this context, Life Cycle Assessment (LCA) emerges as an essential tool for quantifying the environmental impacts of products and processes, enabling the identification of improvement opportunities and comparison between different technologies. One important environmental impact related to climate change is the Global Warming Potential (GWP 100), which, according to the updated IPCC methodology (2021), measures greenhouse gas emissions throughout the product's life cycle. Applying LCA is fundamental to understanding the real environmental benefits of recycling strategies compared to producing virgin material [2].

This study aimed to assess the environmental impacts of recycling PA12 parts and prototypes produced using Powder Bed Fusion (PBF) technology in the HP Multi Jet Fusion (MJF) 5210 printer. Using the Life Cycle Assessment (LCA) methodology, with emphasis on the carbon footprint, the study sought to quantify the environmental benefits of post-consumer recycling of these materials. The results aim to contribute to developing circular economy strategies in additive manufacturing.

2.Methodology

2.1. Recycled PA12 Pellets

Pellets are small spheres or cylinders of granulated plastic, typically 2 to 5 mm in diameter, used as raw material in plastic processing operations. The LCA target in this study is the process of manufacturing PA12 pellets from the recycling of post-use prototypes and parts produced by 3D printing on the HP MJF 5210, at the Additive Manufacturing Bureau of Cimatec Park. The growing volume of printed and discarded parts demanded a sustainable management solution, which motivated the development of this research.

2.2. Life Cycle Assessment (LCA)

2.2.1Product System

The product system considered in the LCA consists of five main processes, four powered by electricity: Cascalheira Milling (industrial mill Mecanofar 230); Cimatec Park Milling (pilot-scale mill Mecanofar 160); Manual Washing; Drying (bench oven MedClav Mod1 11L); and Extrusion/Pelletizing (bench extruder and mini-granulator AxPlásticos).

The process began with Cascalheira Milling, the first fragmentation stage, in which prototypes were broken into coarse PA12 flakes. Next, Cimatec Park Milling further reduced flake size to less than 4.75 mm. After milling, the material underwent washing to remove impurities such as oils, greases, dust, and residual virgin PA12 powder adhered to internal surfaces of hollow parts, using neutral detergent and running water.

Drying followed, with flakes placed in an oven in two stages: first, for eight hours at 70 °C, then homogenized and dried again for 16 hours at 100 °C to ensure adequate moisture reduction. Finally, the fully dried material underwent extrusion and pelletizing. In this stage, PA12 flakes were transformed into a filament of variable diameter and immediately granulated, resulting in PA12r pellets ready for reuse. The flowchart containing the steps can be seen in Figure 1.

2.2.2. Software and Database

The LCA was carried out using OpenLCA software version 2.4.0 and the Ecoinvent 3.10.1 Cut-off database. Primary data were obtained through direct measurements during recycling stages. Equipment energy consumption parameters were estimated from manufacturer technical specifications and machine operating times for each step. Secondary data from Ecoinvent were also used and adjusted to better represent the real process conditions. The data inputs used for the production of 1UF of PA12r pellets were summarized in the inventory presented in Table 1.

Figure 1: Product system related to the mechanical recycling process of prototypes and parts printed in PA12

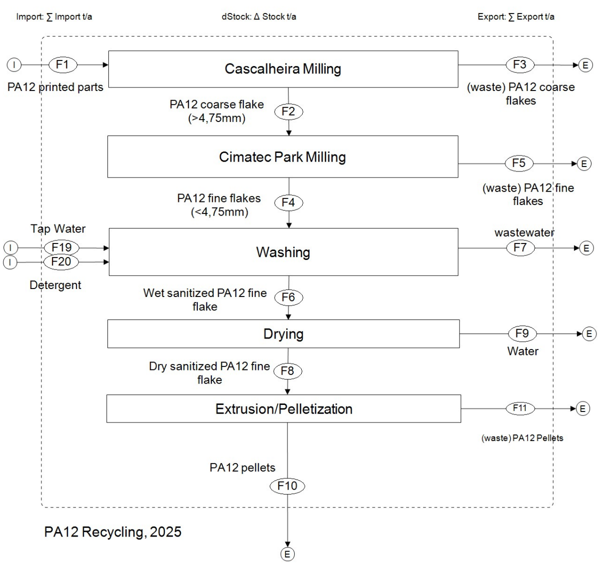


Table 1: Inputs and outputs for the production of 1kg of PA12r pellets

Item	**Intermediate and elementary flows in Ecoinvent v3.10.1**	**Required amount**	**Unit**
Inputs			
PA12 printed parts	**-**	**1,10**	**kg**
Electricity	market group for electricity, low voltage | electricity, low voltage | Cutoff, U - BR	71,89	MJ
Detergent	market for non-ionic surfactant | non-ionic surfactant | Cutoff, U - GLO	0,04	kg
Water	market for tap water | tap water | Cutoff, U - BR	12,38	kg
Outputs			
PA12 pellets	**-**	**1,00**	**kg**
Plastic Waste	treatment of waste plastic, consumer electronics, sanitary landfill, wet infiltration class (500mm) | waste plastic, consumer electronics | Cutoff, U - GLO	0,14	kg
Wastewater	market for wastewater, unpolluted | wastewater, unpolluted | Cutoff, U - RoW	0,01	m^3

2.2.3. Data Quality and Uncertainty Propagation

Uncertainty quantification was performed using the Pedigree Matrix, as proposed by Weidema and Wesnæs (1996). Uncertainty propagation was estimated via Monte Carlo simulation with 5,000 iterations and a 90% confidence interval. This combined approach strengthened the representativeness of the data and contributed to the robustness and reliability of the results [5].

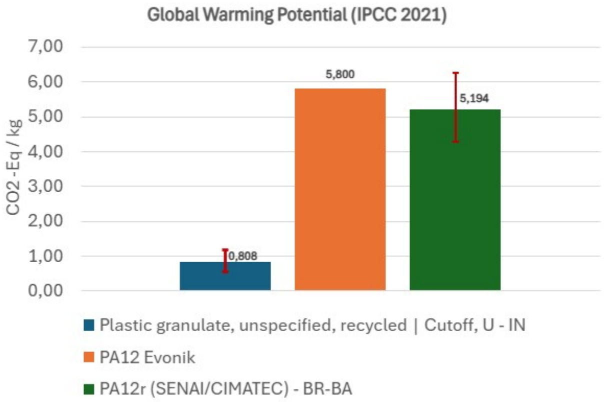
3. Results and Discussion

3.1. Life Cycle Impact Assessment (LCIA)

For comparison purposes, the carbon footprint of virgin PA12 for the same functional unit was obtained from the Plastics Database [6]. The first LCIA analysis compared the environmental impact of producing virgin PA12 granules and PA12r pellets.

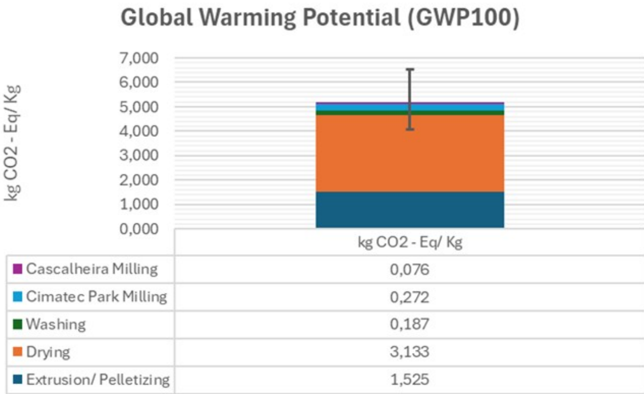
Results showed that PA12r pellets presented environmental advantages over virgin PA12. The recycling process developed at SENAI/CIMATEC recorded emissions of 5.19 kg CO_2 eq/kg of PA12r, representing a reduction of approximately 10% in carbon footprint (Figure 2).

Figure 2: Climate Change Impact Category LCIA for the production of recycled granulated plastic, Evonik granulated PA12, and recycled PA12 pellets at SENAI/CIMATEC



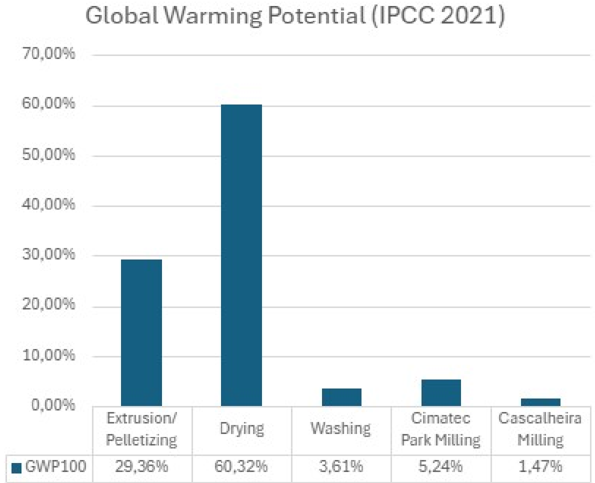
The LCIA results, referring to the different stages of the PA12 recycling process, can be observed in Figure 3. The interpretation of the data showed a significant variation in environmental impacts throughout the process, with emphasis on the Drying and Extrusion/Pelletizing stages for presenting considerably higher environmental loads when compared to the Milling and Washing stages.

Figure 3: Global Warming Potential (GWP100) for the production of 1 kg of recycled pellets



The comparative analysis of the process stages revealed a large variation in environmental impacts, with the Drying stage generating carbon emissions 51.32% higher than the Extrusion/Pelletizing stage. This quantitative difference allows the identification of Drying as the most critical stage in environmental terms in the recycling process. In contrast, the Cascalheira Milling stage showed a modest contribution to the total environmental impact, representing only about 1.5% of the global ecological load of the process. For a comprehensive understanding of the distribution of impacts, Figure 4 presents the relative performance of each stage for the assessed impact categories. It is noteworthy that the results presented correspond to an experiment that was developed mostly on a bench scale. Only the Cascalheira Milling stage used industrial-scale equipment.

Figure 4: Relative carbon footprint results for each stage of PA12 prototype recycling



The highest CO_2-Eq/kg values appeared in the Drying stage; however, when analyzing the operating time, it is observed that the Extrusion/Pelletizing stage presented more significant emission results. CO_2 emissions were significantly higher in the last stage of the process, reaching 0.46 kg CO_2-Eq per hour compared to 0.13 kg CO_2-Eq per hour in Drying—a difference of about 3.5 times greater. Drying showed the highest total impacts due to the prolonged oven time, but Extrusion/Pelletizing proved to be the most demanding process in operational terms.

The carbon footprint identified in this LCA arises mainly from electricity consumption, considering both direct use by equipment and the predominantly hydroelectric Brazilian energy matrix. The current project allows adjustments to optimize results, either through scaling up to an industrial level or using renewable energy sources.

All values presented here were calculated based on the Cut-off approach, which disregards the environmental impact associated with the input of recycled material, assuming that this impact has already been accounted for in the original part's life cycle. On the other hand, the Product Environmental Footprint (PEF) methodology makes it possible to allocate burdens and credits between the supplier and the user of recycled materials through the Circular Footprint Formula (CFF), which integrates aspects related to material, energy, and disposal. The CFF ensures that both the impacts associated with the recycled content present in the product (R1) and its recyclability at the end of its useful life (R2) are considered, avoiding double counting and providing a more accurate environmental assessment. Although this methodology has not yet been implemented in LCA software, it is likely to be incorporated in the near future, making the allocation process of impacts in product life cycles more aligned with the reality of recycling and recyclability [7].

It is important to note that the literature review conducted for this work revealed the absence of specific studies on polymer recycling from additive manufacturing. This finding shows that research related to the circularity of parts and prototypes manufactured by this technology, as well as their environmental impacts, is still at an early stage, representing a relevant scientific gap in the area.

4. Final Considerations

This study analyzed the life cycle of recycling 3D-printed PA12 parts and prototypes using powder bed fusion on an HP Multi Jet Fusion printer. The chosen impact category was Climate Change – Global Warming Potential (GWP100) (IPCC 2021). The system boundary followed a cradle-to-gate approach, covering raw material extraction to production, before product distribution.

The proposal to produce PA12r pellets was supported by the possibility of using the recycled material in various manufacturing methods (additive and conventional), ease of production with available equipment, and lower operational complexity compared to producing 3D printing filaments.

The Life Cycle Assessment (LCA) results revealed significant findings about the PA12 recycling process, demonstrating environmental advantages compared to conventional production. It was found that the bench-scale process for producing recycled PA12 pellets showed superior environmental performance to virgin granulated PA12 production, particularly regarding carbon footprint. This result suggests that scaling up the process to industrial levels could generate substantially lower environmental impacts, reinforcing its sustainable potential.

The analysis identified the Drying stage as the most critical phase of the recycling process, followed by the Extrusion/Pelletization stage. Quantitative data showed significant differences, with values slightly exceeding 50% between these stages. Specifically, Drying emerged as the phase with the highest total impacts, mainly due to the extended operation time of the oven. On the other hand, Extrusion/Pelletization proved to be the most operationally demanding process, requiring greater attention for potential efficiency improvements.

From an environmental perspective, recycling PA12 prototypes is particularly relevant as it provides proper material destination, avoiding negative environmental impacts. Instead of being disposed of in landfills, the waste is transformed into recycled pellets, which re-enter the production cycle as secondary raw material. This mechanism not only prevents waste generation but also promotes material circularity, aligning with circular economy principles and contributing to more sustainable production systems.

Thus, despite process scale limitations, recycling PA12 parts and prototypes from additive manufacturing shows great potential for developing products using PA12r pellets.

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